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**14. ABSTRACT**

This report results from a contract tasking M.V. Lomonosov Moscow state university as follows: The modernization of our experimental installations will be fulfilled.
Optimal for applications types and compositions of liquid and solid dielectrics will be determined.
Solid dielectric effective separation conditions at the sliding discharge realization over the separation boundary of solid dielectrics with different values of dielectric permeability will be determined.
Fuel-air mixture modification process (decomposition to radicals) under sliding discharge plasma impact will be investigated.
Theoretical model of gas excitation by the sliding discharge will be created.
Theoretical model of initial stage of the sliding discharge; investigations of optimization possibility of sliding discharge parameters during unfinished and finished stages will be created.
Sliding discharge physical model will be developed.
Distribution of gas dynamical parameters in the supersonic channel with a reverse step will be investigated.
The ignition and combustion of supersonic flows of gaseous fuels, stabilized with a help of combined discharges created in an aerodynamic channel with and without a reverse step will be studied.
The influence of stoichiometry of a fuel-air mixtures, way of a fuel supply into aerodynamic wind tunnel, pressure, input electric power, discharge pulse duration, mode of excitation of the gas discharge, reduced electric field, electron and gas temperature, ultra-violet radiation of plasma of the gas discharge created in supersonic stream on the reduction of an ignition delay and on improvement of completeness of combustion of supersonic fuel-air streams will be investigated.
The detail investigation of the influence of the charged and active particles on reduction of an ignition delay and on increasing of completeness of fuel-air mixture combustion will be researched.
The non-equilibrium kinetic model, which takes into account the influence of ultra-violet radiation, charge particles and chemically active radicals on process of ignition and burning of supersonic fuel-air streams initiated by combined electrode discharges into aerodynamical channel with stagnant zone, will be developed.
The main mechanisms and channels resulting in fast ignition and burning of supersonic hydrocarbon-air streams will be revealed.
The final scientific report will be prepared.

**15. SUBJECT TERMS**
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**QUARTER TECHNICAL REPORT**

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**(From March 01, 2007 to May 31, 2007)**

# FUNDANENTAL INVESTIGATIONS OF SURFACE DISCHARGES OVER DIELECTRIC LIQUIDS FOR IGNITION AND COMBUSTION OF FUELS

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**Contents**

**Abstract**



## Abstract

1. Results of experimental works with the electrode discharge are represented, namely:

- electrode discharge experiments formulation and test realization over a fluid (water as testing liquid); formulation of experiments and test measurements of break down voltage over water.

2. Results of experimental works with the surface RF discharge are represented, namely:

- surface microwave discharge experiments formulation and test realization over a fluid.

3. Results of experimental works with the capillary discharge are represented, namely:

- capillary discharge near liquid surface experiments formulation and test realization over a fluid (water); measurements and estimates of its parameters.

## Introduction

Nowadays a problem of effective ignition and combustion of fuels is facing a development of new aircraft generation. Active search of new effective and reliable ways of flammable substances ignition in the high-speed flows takes place in different laboratories, which allows to considerably improve combustor chambers and engine characteristics [1-2].

By now a great number of experiments on ignition and combustion of gaseous hydrocarbon fuels were realized with a help of different gas discharges, but questions of combustion activation and ignition of liquid hydrocarbon fuels with a help of plasma are investigated much smaller, but they are closer to real conditions. Questions of discharge development over surfaces of liquid fuels and dielectric liquids are practically uninvestigated yet.

Known works [3-6] devoted to electrohydrodynamic flows consider disturbances of charges liquids in conditions of electric and magnetic fields. Main effects are connected with ion impact of electric corona, questions of discharge development over liquid surface and ignition are not considered in them. In close to plasma conditions one can consider ion wind, appearing near highly charged electrodes [5-6], at that the ion wind velocity is dependent on polarity of applied constant voltage and reaches, for example in air, value 5-6 cm/s at applied voltage ~ 6-8 kV. Usually impact of processes in air on those in liquid are not considered. Though experiments in liquids show [5] vortices and other structures development in them. Difficulties of experimental formulation and theoretical analysis [3-6] leads to a situation when there is almost no theoretical models of two charged -liquids impact. There is also almost no works on development of liquids under supersonic air motion over them, the same situation is with respect to charged. So there is a necessity in development of corresponding works basing on results of classical electrodynamics and hydrodynamics [7-9], connected with, so called, Tonks - Frenkel and Raleigh – Taylor instabilities.

Influence of ion wind is under a discussion in works [10-11]. It is shown in them that ion wind increases of gas warming, improves mixing of gases, excites some internal levels of freedom of molecules, and in general this decreases ignition activation energy.

One of few works connected with discharges over liquids [12] considers development of the glow discharge over the surface of a liquid (water, kerosene) at different location of electrodes. Sometimes for stability some organic material (filter cellulose) is impregnated by the liquid. Electrohydrodynamic effects leading to the liquid spraying are excluded at such formulation of experiments, however measurements of breakdown fields over the liquid is possible. In the case of

water surface the breakdown field proved to be ~10 kV/cm, it is by 3 times smaller than those of the dry air.

In works [13-15] experiments of our team was undertaking of ignition of different hydrocarbon materials (including heavy hydrocarbons and alcohol) in conditions of pulsed, glow, open and capillary discharges, which showed high efficiency of ignition with their help. At the processes of diffusion of liquid vapors lead to substantial increase of interaction area between plasma and gaseous mixture. The flame front often takes a complicated form.

In the present work we start to investigated processes over liquids: water and alcohol (dielectric fuel) and their mixtures- which showed their convenience in experimental conditions. We use water and water-alcohol mixtures to easily visualize hydrodynamic processes over and on the liquid surface; then we repeat these experiments with pure alcohol (and some other dielectric liquids). After these experiments we undertake combustion experiments with pure alcohol (and some other dielectric liquids).

In particular in this work we undertake experiments with surface electrode discharge, surface microwave discharge and erosive-capillary discharge.

## 1. Results of experimental works with the electrode discharge. Formulation.

**Formulation of a problem on measurements of breakdown characteristics.** At undertaking of experiments on investigation of electrode discharges (pulsed or on a constant current) over a surface of liquids, breakdown voltage value, at which in essence the discharge begins, is one of the important parameters. For determination of breakdown characteristics of the electrode discharges over a surface of liquids we developed an experimental construction, which design is represented in Fig. 1.

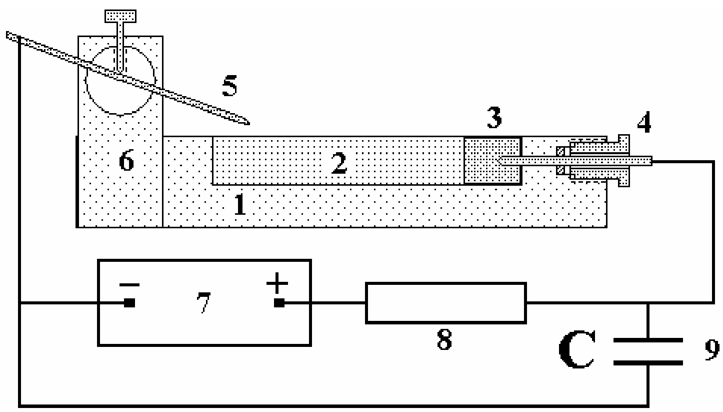



***Fig.1.1. An experimental construction for determination of breakdown characteristics.***

In a basement (position (1) in Fig.1) made of organic glass we cut a cavity of rectangular cross section which was filled with investigated liquid (2). Flat electrode (positive, anode) is placed directly in the liquid, which is connected with power source through hermetic unit (4). Another electrode (cathode (5) ) is fixed in a special device (6), which allows to change this electrode position both in horizontal and vertical planes.

We use a high voltage rectifier (7) as the feeding source of the electric source, that allows to vary voltage on electrodes from 2 kV to 50 kV with a step of 250 V. For limiting of the discharge current appearing at the breakdown, we use a ballast resistance (8), which value is 300 MΩ. For more precise determining of the breakdown moment and corresponding value of the breakdown voltage we use additional capacity (9) ~ 500 pico F. The breakdown moment is fixed by appearance of the glowing spark channel between the cathode and the surface of a liquid, and also by corresponding sharp drop of the voltage value on the additional capacity, see Fig.2.

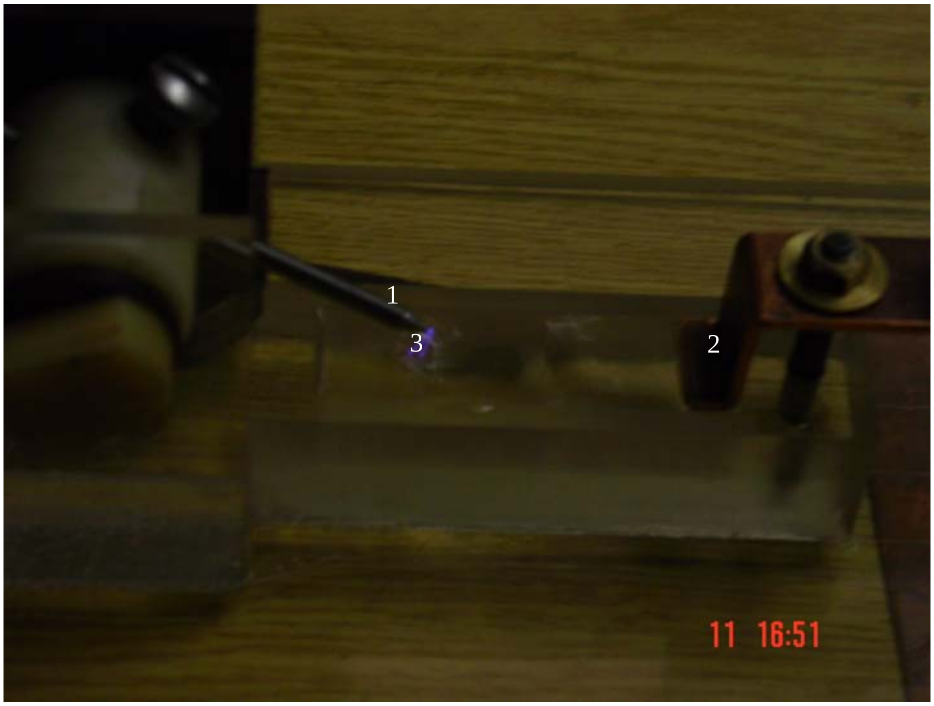



***Fig.1.2. Fixation of the breakdown. 1-cathode, 2 anode, 3-discharge channels.***

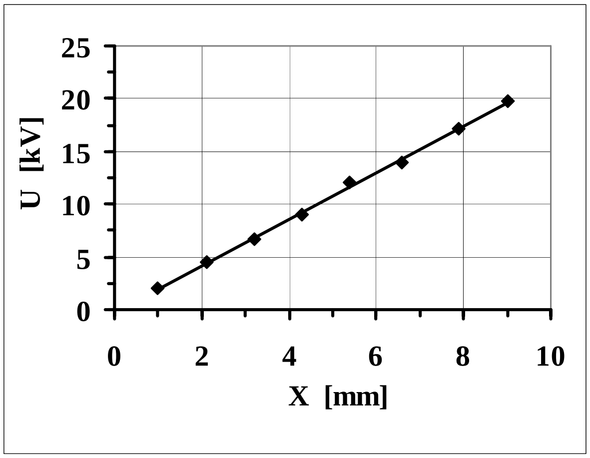



***Fig. 1.3 Results of measurements: breakdown voltage via the distance between the cathode and the water surface.***

With a help of this set up we undertook control tests on determination of breakdown characteristics in the case when ordinary water tap water. Water, which was in the cavity made additional resistance of about 1,5 MΩ, which was considerably smaller than the ballast one. The cathode in this case was placed at the angle of $50^0$ to the vertical. Results of such measurements are represented in Fig. 10, in which one can see breakdown voltage dependence via the distance between the cathode and the water surface.

From the represented dependence one can see that the breakdown voltage value rises practically linearly with increase of the distance between the cathode and the liquid. Breakdown electric field experimental value proves to be E≈22 kV/cm, which is smaller than those of the dry air E≈27 kV/cm, this result is in disagreement with reference [12] ; this shows that there is a necessity of additional experiments in understanding of this fact..

**Investigations of electrode discharge over liquid surface, problem formulation.**

For undertaking of experiments on investigation of electrode discharges over surfaces of liquids we use a cavity, which cavity was described in details above. Sizes of the cavity, to which investigated liquid is placed, are in our case 70×20×15 mm with respect to length, width and depth. Electrodes of 4 mm diameter are made of stainless steel. A discharge between these electrodes is created with a help of the high voltage generator of pulses, which allows to realize pulses with duration from 10 to 1000 μs. Maximum amplitude in the pulse changes from 5 to 20 kV, this realizes a possibility to vary a discharge current value in the range (1 – 20) A at application of additional set of ballast resistances.

I. For visualizing of discharge picture we use a high-speed CD camera and pulsed source of lighting (flash lamp). CD camera frame duration can be varied from ≈ 3 μs to ≈ 1 s at repetition frequency of 50 frames per second. Minimum duration of the flash lamp gun pulse is 10 μs, and the maximal is ~ 600 μs.

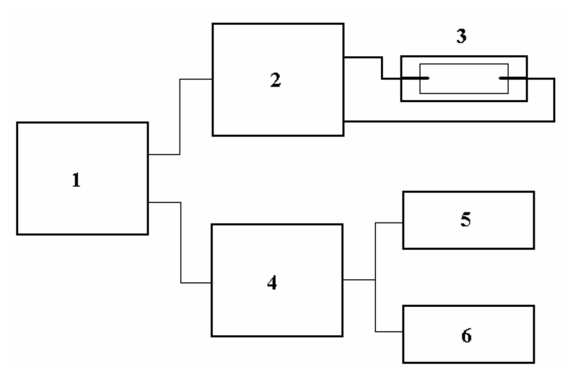



Fig. 1.4.

For synchronization of pulsed high voltage source work, flash lamp gun, and CD camera we developed a synchronizing system, which scheme is represented in Fig.4. A principle of this scheme work is the following. The setting generator (1) makes pulses for starting of the high voltage pulse source (2), which makes pulses for creating of the discharge in the cuvette (3). Simultaneously the starting pulse

from the same generator comes to the generator of delayed pulses (4). From its output signals for starting of flash lamp gun (5) and CD camera (6) are given. The setting generator determines a duration of the discharge pulses between electrodes in the cuvette. The generator of delayed pulses is used for creation of time shift between the discharge pulse and the flash lamp gun and CD camera actuation time. Delayed time value can be varied in rather wide limits: from tens of microseconds to units of seconds. Such great interval of delay allows to investigate not only the discharge picture, but spatial evolution of drops and vapors of liquids, flowing out with relatively small velocity from the cuvette during and after the discharge.

## 2. Surface microwave (RF) discharge

Surface microwave discharge was earlier created in our laboratory for solution of some problems of supersonic plasma aerodynamics, namely, for optimum energy delivery to the boundary layer, appearing at supersonic flow streamlining a body. It was shown that application of surface microwave discharge allows to change flow characteristics near a body, in particular, to change local coefficient of turbulent friction. The second problem, which can be solved with a help of surface microwave discharge consists in quick inflammation of supersonic gaseous air-propane mixture flow. It was earlier shown that the induction period for inflammation of air-propane mixture supersonic flow decreases to 5-10 μs at application of this discharge.

Remember shortly a scheme of surface RF discharge creation. It is known that electromagnetic energy delivered to a system transforms to the surface wave at creation of RF discharge inside a tube with dielectric walls filled with a gas. At that self consistent system appears when plasma medium created by the surface wave is necessary for existence of this surface wave. The wave propagates in a space until its energy is sufficient for creation of the plasma with electron concentration no smaller than the critical concentration $n_{ec}=m(\omega^2+\nu^2)/(4\pi e^2)$, where $e$ and $m$ are the electron charge and mass, $\omega$ is circular field frequency, $\nu$ is frequency of electron-neutral molecule collisions in the gas. The surface wave does not penetrate beyond the boundary of the space area, where electron concentration decreases to the value of $n_{ec}$, and the surface discharge does not exist in these places. The given means of plasma creation and a device for its creation is called surfatron. This means is rather deeply investigated and widely used, for example, in plasma chemistry. In this case we have a system plasma-dielectric- free space, i.e a plasma created by the surface wave and limited by the walls of the dielectric tube separating the plasma and the free space surrounding the discharge tube exists inside the discharge tube filled by a gas at low pressure. We proposed to turn this system inside out. In this case a dielectric was inside the system and plasma is created over its surface, existence of which is maintained by the surface RF wave.

First experiments were made with Teflon antenna. It was experimentally shown that required pulsed power for creation of surface RF discharge in the pressure range 0,1-50 Torr was 10-20 kW whereas the RF pulsed power required for initiation of the discharge at atmospheric pressure is about 250 kW.

It is clear that it is necessary to look for a way to decrease a level of the pulsed power, and one of forth coming problems consists in modernization of the surface RF discharge initiation system,

which is aimed at substantial decrease of delivered power required for creation of such a discharge at atmospheric pressure.

Experiments on inflammation initiation of different flammable mixture in conditions of surface RF discharge will be executed with a help of the set up block-scheme of which is represented in Fig.1. We applied this set up for investigation of surface RF discharge features in different motionless gases in wide range of pressures from 1 mTorr to 100 Torr. However, since volatile liquids located in vacuum chamber quickly evaporate then it is initially undertake investigations at atmospheric pressure of air.

The microwave source is a pulsed magnetron generator operating in the centimeter wavelength range. The parameters of the magnetron generator are as follows: the wavelength is $\lambda$=2.4 cm, the pulsed microwave power is $W_p$<100 kW, the pulse duration is $\tau=(1\text{-}200)\cdot 10^{-6}$ s, and the period-to-pulse duration ratio is Q=1000, thus mean power did not exceed 100 W. The magnetron is powered from a pulsed modulator with a partial discharge of the capacitive storage. Microwave power was delivered to the discharge chamber through a 9.5x19-mm rectangular waveguide. The input microwave power was measured with the help of a directional coupler installed in the waveguide so that a fraction of microwave power was directed to the measuring arm containing an attenuator and a section with a crystal detector. The microwave pulse envelop at the detector output was recorded using a digital oscilloscope. The pulse envelop was nearly flat-top. The same signal was fed to a pulsed digital voltmeter measuring the pulse amplitude. The voltmeter was preliminarily calibrated with the help of a calorimetric power meter connected to the output of the main arm of the directional coupler. All the components of the microwave transmission line were sealed. To avoid electric breakdowns inside the waveguide, it was filled with an insulating gas ($SF_6$) at a pressure of 0.4 MPa. The vacuum system allowed to carry out experiments at air pressures of $p=10^{-3}\text{-}10^{3}$ Torr.

It is known that if a discharge is initiated by any means then it exists long time at power much smaller than those necessary for the gas breakdown. There are many means of RF discharge initiation, for example: laser spark, spark discharge; irradiation of area where the discharge is planned to be created by vacuum ultra-violet radiation; application of different metallic initiators, wires, dipoles, etc.

The contact metal – dielectric is also very effective for RF discharge initiation. We plan to change the Teflon antenna for the quartz one, and to change RF energy delivery to the quartz antenna unit.

First experiments have given encourage results and allowed us to create surface RF discharge at

power 10-20 kW at air pressure of  760 Torr.

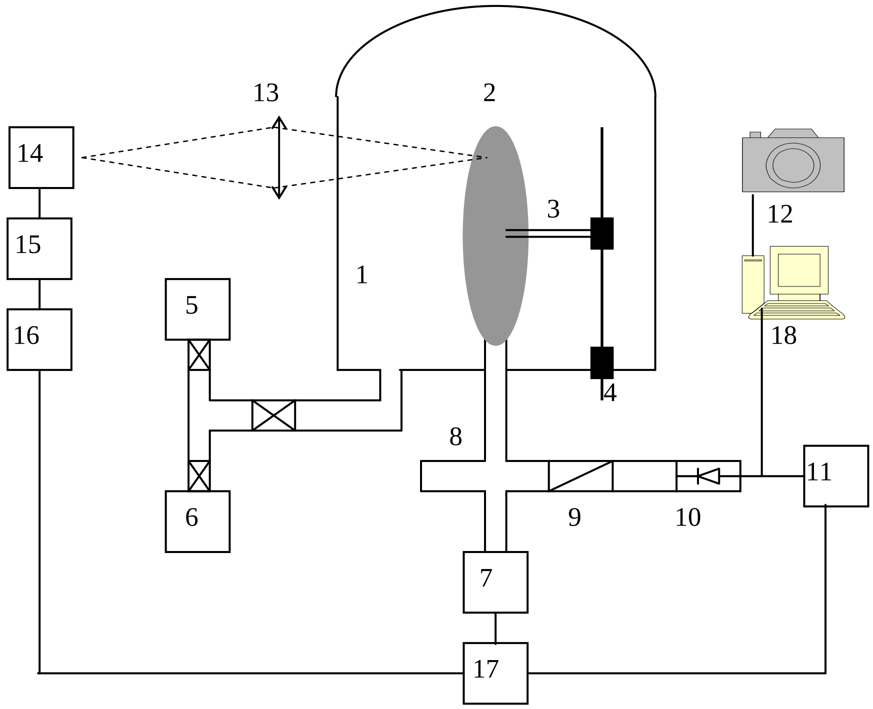



Fig. 2.1. The block- scheme of the experimental installation. 1 – the discharge chamber; 2 – a surface microwave discharge on the dielectric antenna; 3 – a double probe; 4 – system of fastening and moving of a double probe; 5 – a pumping system; 6 – a cylinder; 7 – the magnetron generator; 8 – a directional coupler; 9 – attenuator; 10 – a crystal detector; 11, 16 – digital oscilloscopes; 12 – a digital photo camera; 13 – system of lenses; 14 – spectrograph; 15 – the photo electronic multiplier; 17 – the block of synchronization; 18 – a personal computer.

## 3. Results of experimental works with the capillary discharge. Formulation.

**Formulation of experiments with capillary long plasma generator.** This discharge was firstly described in [15]. This discharge is of interest connected with simple realization (the discharge realizes a plasma area over a cuvette filled with a liquid). It has high electron and gas temperatures [16] promoting mixing of vapors with air and their ignition and possibility of gasdynamic disturbances observation on the surface of a liquid.

Long capillary discharge (LCD) has been designed so that a cavity between electrodes was easily filled with different liquid substances.

**Capillary long plasma generator**.

Principle scheme of Long capillary plasma generator (LCD) is represented in Fig.3.1. Its connection scheme of connection with power block is represented in Fig. 3.2. LCD is made of organic glass (PMMA, which melting temperature is T~ 120-130$^{o}$ C), material of electrodes is copper, graphite; erosive insert is organic glass.

A cuvette – a cavity for location of working liquids has the following sizes 142×10× 6 mm. Comparably long length of a channel with respect to conventional capillary plasma generators was chosen to observe possible motion of a liquid and development of hydrodynamic processes.

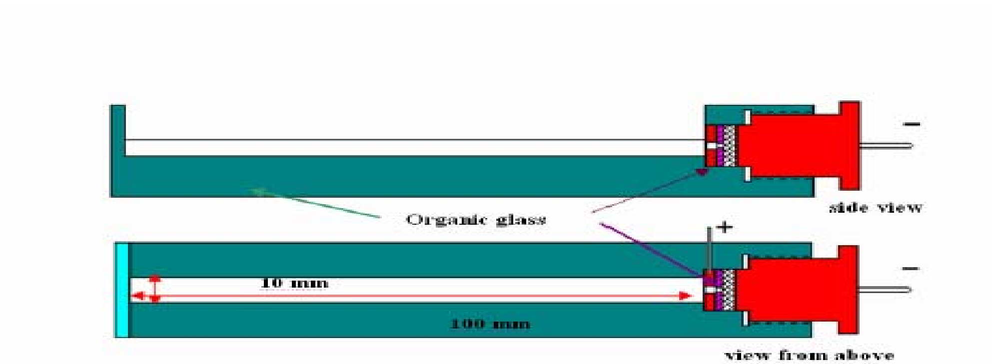



***Fig. 3.1 Principle scheme of long capillary plasma generator (LCD)***

A principle scheme of this plasma generator circuit is represented in Fig.3.2. It represents a circuit including initiating capacity, a commutator, creating an initiating breakdown and a discharge device. In Fig.3.3 one can find typical temporary dependencies of current and voltage in the discharge; they allow to evaluate maximum values of the voltage and the current: $U_{max}$=240 B, $I_{max}$=1,8·10$^{3}$A, and by integrating obtain energy stored in the discharge: E=390 J. These characteristics show that the discharge operation time is $t_{dis}$≈10 ms.

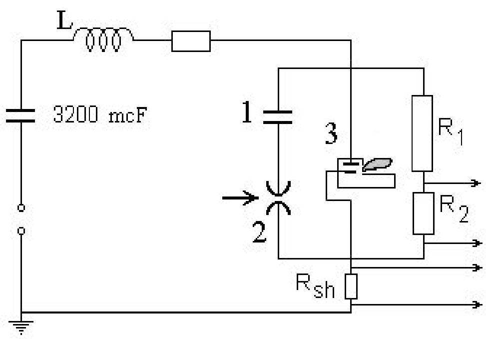



***Fig. 3.2. Principle scheme of the circuit with capillary long plasma generator.*** *1 – initiating capacity; 2 –a commutator creating the initiating breakdown; 3 – a capillary, $R_1$, $R_2$ – resistances of the voltage divider.*

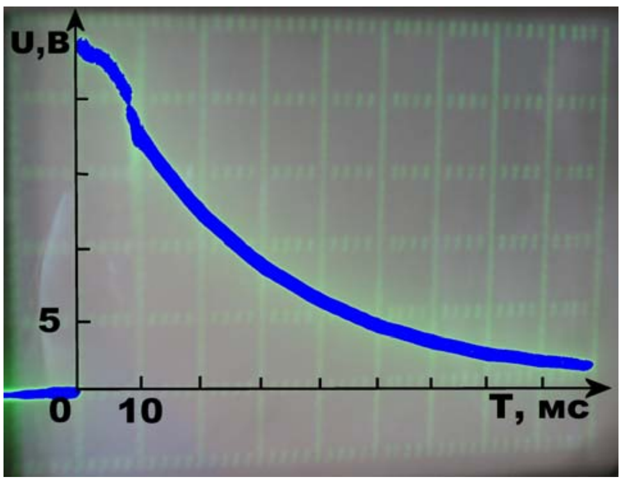



***Fig. 3.3. A typical U(t) –voltage temporary dependence (relative units) dependence.*** *Maximum value of voltage 240 V one gets at accounting a division value 50 V/div .*

Energy of the discharge is close to those realized in works [16-17], so we can expect close plasma characteristics at the exit from the plasma generator channel. For example we represent measurements of temperatures and electron concentrations in the stream, created by the analogous plasma generator with the capillary of PMMA [16]. In Fig. 3.4 one can see an axial, Fig. 3.4a, and radial, Fig. 3.4b, distributions of the electron concentration in the plasma stream. At that high concentrations of ions (electron concentration equals to those of ions) can realize impulse impact on air. In Fig. 3.5. one can see the axial, Fig. 3.5.a, and the radial, Fig. 3.5.b temperature distributions in the plasma stream. These figures show realization of high temperature in the plasma generator's channel, which can realize also thermal impact on hydrocarbon gases.

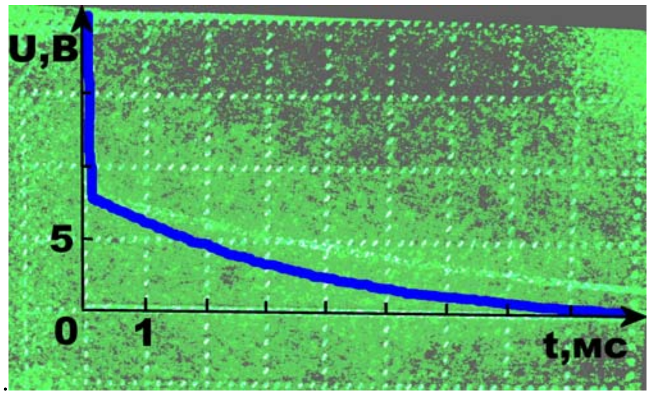



***Fig.3.3b. A typical I(t) – current temporary dependence (relative units) dependence.*** *Current characteristic obtained from the calibrated resistance (75 mV=3 A). Maximum current value is I = 800 A.*

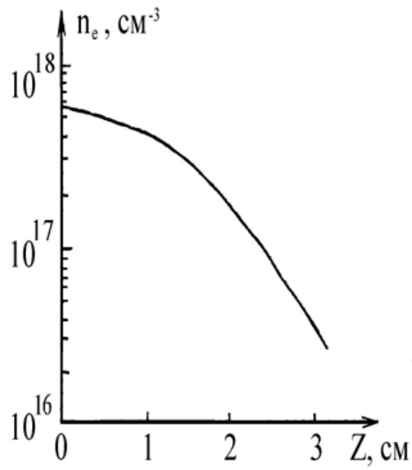



Fig.3.4. a

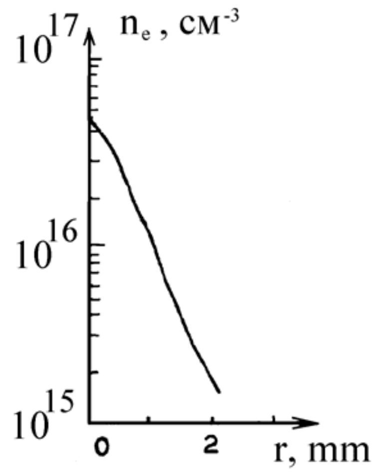



Fig.3.4. b

***Fig. 3.4. Electron concentration distribution in the plasma stream. a – axial, b – radial.***

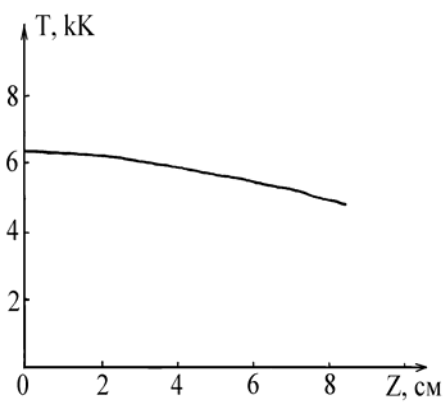



Fig.3.5. a

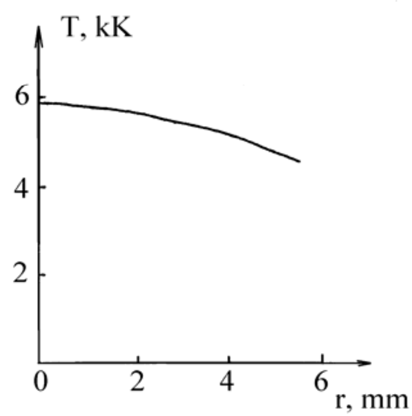



Fig.3.5.b

***Fig. 3.5 Temperature distribution in the plasma stream. a – axial, b – radial.***

In Fig. 3.6 one can see the appearance of the set up.

In Fig.3.7 one can see a typical photo of the discharge over organic glass flask. It was made with exposure of 3 seconds. The stream diameter proves to be about 9 mm, and exposed area-represents vapors of organic glass. So the erosive discharge represents a narrow plasma stream flowing into the atmosphere.

In experiments we used 9-frame camera K011, with the following characteristics: frame duration 0,1 – 100 μs, inter frame pause 0,1 – 100 μs. It allowed to investigate in details the stream propagation. Consequence of images in frames is: from the left to the right and up-down.

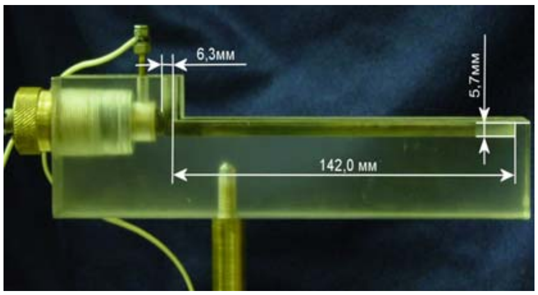



*Fig.3.6. Appearance of capillary long plasma generator.*

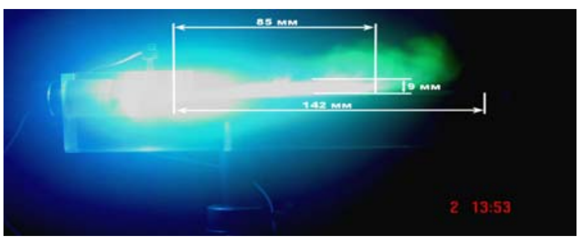



*Fig.3.7. Integral photo of a discharge with application of a light filter.*

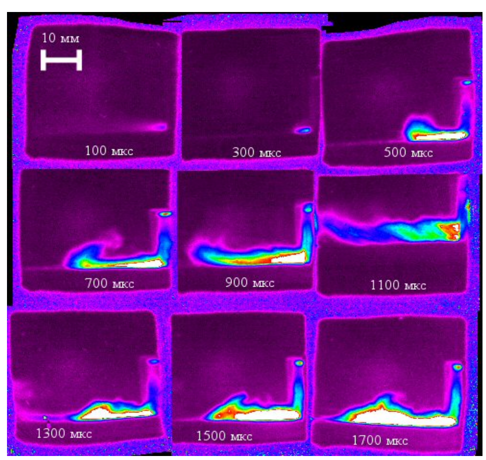


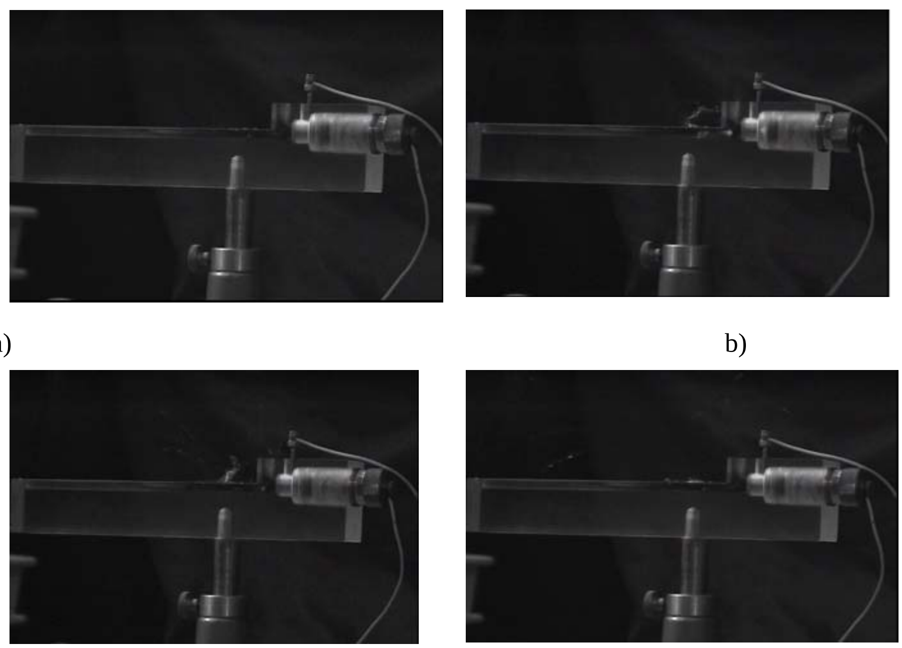

***Fig.3.8. First 1700 μs of the plasma stream propagation (100,100,0).***
***Size in the frames is in mm, time moments are in μs.***

In Fig.3.8 one can see first 1700 $\mu s$ of the plasma stream propagation. Plasma stream length at this moment is ~ 30 mm. So the discharge velocity at initial stage is ~ 40 m/s, and average velocity in the result of interaction with the atmosphere becomes ~ 20 m/s.

**Erosive discharge over water surface.**

Investigations of erosive discharge stream over water surface were made in order to reveal hydrodynamic effects of discharge plasma-water surface interaction. These investigations we made with a help of video camera, which frame fixing was ~ 0,04 s. In Fig. 3.9 one can see discharge frames over water surface. Water obtains an impulse in the result of water interaction with flowing out mixture of plasma and a gas, and a disturbance moves along the channel filled with water. The estimate of the disturbance propagation in the channel made on a basis of video recording is $V \sim (0{,}28 \pm 0{,}04)$ m/s.

Investigations of erosive discharge stream over water surface were also made with a help of 9-frame camera K011. In Fig. 6 one can see a way of the plasma stream propagation over water in time period 2100 – 3700 $\mu s$ from the starting moment of plasma flowing. One can see in frames that water begins to intensively vaporize, what is characterized by appearance of wider halo over the channel.



a) b)

c) d)

**Fig. 5. a-d. Integral frames of the capillary discharge impact on water**

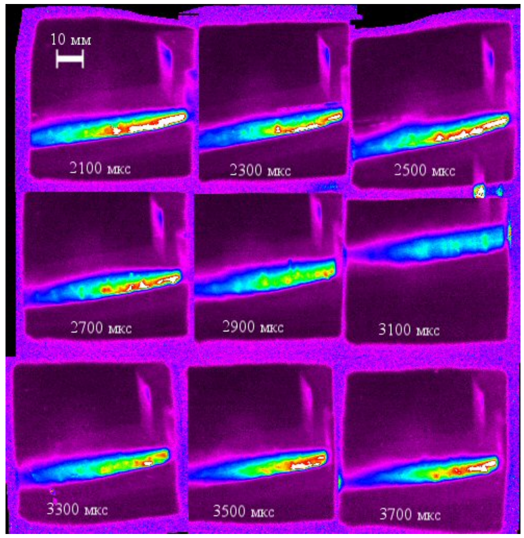



**Fig. 6. Frames of plasma stream propagation over water (100,100,2000) .**
*Size in the frames is in mm, time moments are in $\mu$s.*

## Conclusions

Experimental works with the electrode discharge have been started, namely, electrode discharge experiments formulation and test realization over a fluid (water as testing liquid); formulation of experiments and test measurements of breakdown voltage over water.

Experimental works with the surface RF discharge have been started, namely, surface microwave discharge experiments formulation and test realization over a fluid in atmospheric air

Experimental works with the capillary discharge have been started, namely, capillary discharge near liquid surface experiments formulation and test realization over a fluid (water); measurements and estimates of its parameters.

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